LMSC/D462151
6 October 1975

SECOND QUARTERLY PROGRESS REPORT
(For period ending 23 September 1975)
On
ANALYSIS OF SATELLITE DATA ON ENERGETIC
PARTICLES OF IONOSPHERIC ORIGIN
Contract NASw 2777

This is a program for the analysis of selected data from the Lockheed energetic ion mass spectrometer experiment on satellite 1971-89A. During this reporting period, the progress made is evidenced by the attached paper, entitled "The Morphology of Energetic O^+ Ions during Two Magnetic Storms: Temporal Variations," which has been submitted to the Journal of Geophysical Research. Work is currently in progress on a follow-on paper dealing with latitudinal variations in the measured O^+ fluxes during the same period.

R. D. Sharp

R. D. Sharp, Principal Investigator
Lockheed Palo Alto Research Laboratory

(NASA-CR-145863) ANALYSIS OF SATELLITE DATA ON ENERGETIC PARTICLES OF IONOSPHERIC ORIGIN Quarterly Progress Report, period ending 23 Sep. 1975 (Lockheed Missiles and Space Co.) 35 p HC $4.00 CSCL 04A G3/46

N76-13678

Unclas
15015

THE MORPHOLOGY OF ENERGETIC O^+ IONS DURING TWO MAGNETIC STORMS: TEMPORAL VARIATIONS

R. D. Sharp, R. G. Johnson, and E. G. Shelley

Space Sciences Laboratory
Lockheed Palo Alto Research Laboratory
LOCKHEED MISSILES & SPACE COMPANY, INC.
3251 Hanover Street (52-12/205)
Palo Alto, California 94304

THE MORPHOLOGY OF ENERGETIC O^+ IONS DURING TWO MAGNETIC STORMS: TEMPORAL VARIATIONS

R. D. Sharp, R. G. Johnson, and E. G. Shelley
Lockheed Palo Alto Research Laboratory
Palo Alto, California 94304

ABSTRACT

A study has been conducted of the morphology of precipitating O^+ and H^+ ions in the energy range $0.7 \leq E \leq 12$ keV during the storm-time period from December 16-18, 1971, which encompassed two principal magnetic storms. This paper describes some of the results of this study with emphasis on the temporal variations of parameters characterizing the intensity, average energy, and spatial location of the zones of precipitation of the two ionic species. One of the principal results was the finding that the intensity of the precipitating O^+ ions was well correlated with the geomagnetic indices which measure the strength of magnetospheric substorm activity and the strength of the storm-time ring current. Since the O^+ ions are almost certainly of ionospheric origin the correlations indicate that a previously unknown strong coupling mechanism existed between the magnetosphere and the ionosphere during the storm period. Some other morphological features apparent in the data are: 1) the storm-associated initial increase of the O^+ ions on the nightside (0300 LT) was found to lead that on the dayside (1500 LT) and lag the initial nightside H^+ increase by more than one hour in both

storms; 2) a strong correlation was observed between the variations in locations of the O^+ and H^+ precipitation regions on both the day and nightside crossings; and 3) the average energies of the O^+ and H^+ precipitations were significantly correlated on the dayside crossings. The implications of these results with respect to some phenomenological models of the O^+ morphology are discussed.

The total worldwide precipitated ion energy flux has been estimated during the period of the study and compared to the ring current energy content as measured by Dst. The comparison indicates that ion precipitation was an important loss mechanism for ring current energy during the December 17-18, 1971 magnetic storm.

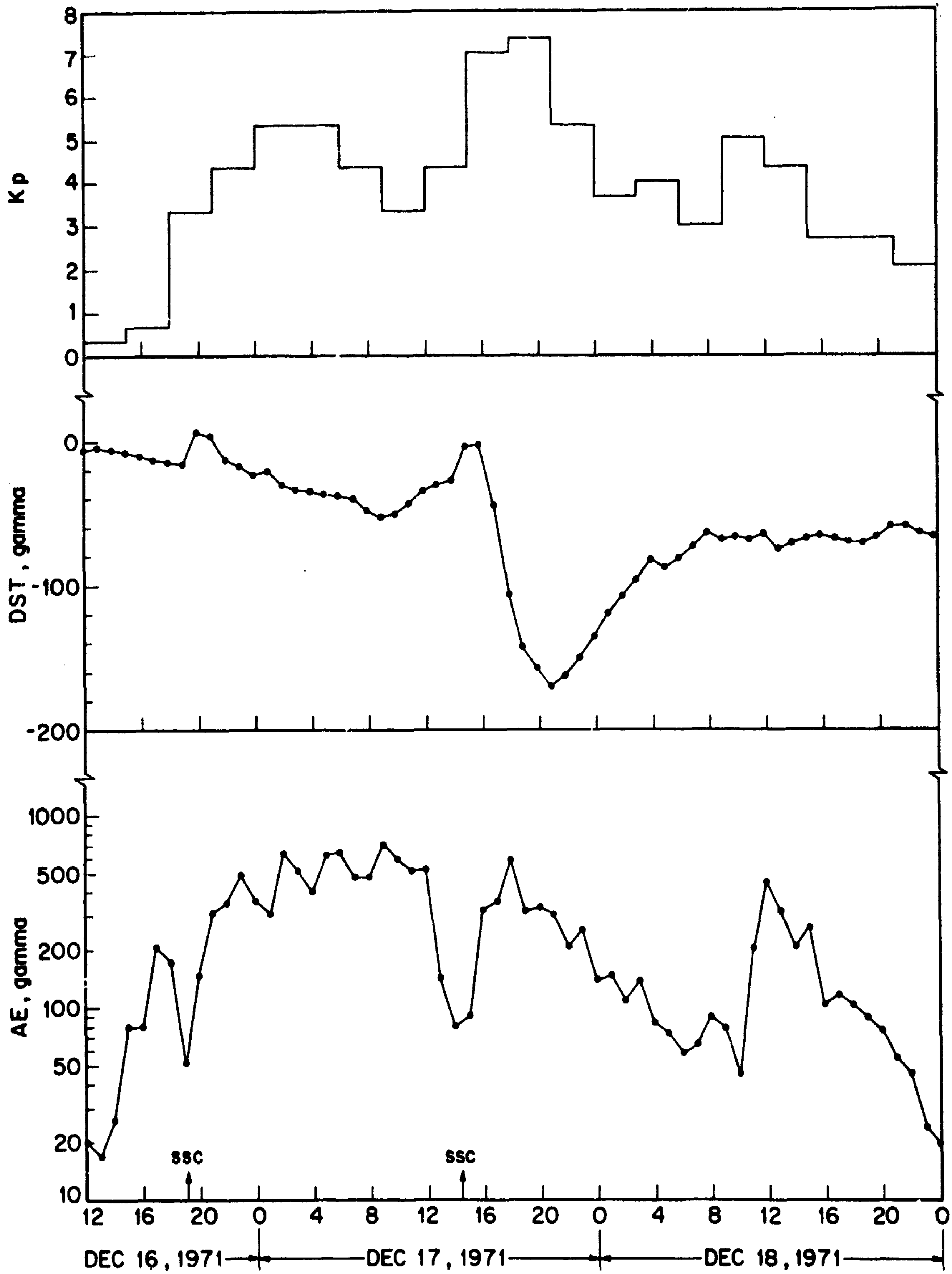
INTRODUCTION

The discovery of O^+ ions with energies of up to 12 keV in the magnetosphere was reported by Shelley et al. [1972]. Synoptic studies of several aspects of the morphology of these ions were described by Sharp et al. [1974], Shelley et al. [1974], and Johnson et al. [1975]. The energetic O^+ ions were inferred to be of ionospheric origin. They were observed in every storm studied over a one-year period and at all local times. They were also observed at reduced intensities during non-storm times. This is the first of two papers which will present more detailed results from a statistical study of the temporal and latitudinal variations of the O^+ ions and the accompanying protons in the same energy range ($0.7 \leq E \leq 12$ keV) during two magnetic storms. This paper will present integral parameters, each characterizing

a single traversal of the precipitation zone. Paper II will describe the latitudinal variations averaged over each of the two storms. A similar statistical analysis of a comparable body of data on auroral electrons and the more energetic component of the auroral protons has been published [Sharp and Johnson, 1968; Sharp et al., 1969].

The two storms studied here occurred in the period December 16-18, 1971. Both were initiated with sudden commencements which occurred at 1904 UT on December 16 and 1418 UT on December 17. The first storm had only a small main phase with a peak Dst of 54γ. The second storm had a classic main phase with a peak Dst of 171γ and a recovery phase lasting until about 2300 UT on the 18th. The relevant geomagnetic indices characterizing this period are shown in Figure 1. Extensive data on the equatorial particle distributions during this same period were acquired by the Explorer 45 satellite [Smith and Hoffman, 1973; Hoffman, 1973; Williams and Lyons, 1974a,b; Lyons and Williams, 1975; and Williams, 1975].

The data presented here were obtained from an energetic ion mass spectrometer experiment on the low-altitude polar satellite 1971-089A. The experiment contained three spectrometers. Each consisted of an electrostatic analyzer in series with a crossed field velocity filter which provided both mass-per-unit-charge and energy-per-unit-charge information on the measured particles. The satellite was in an approximately circular orbit of 800 km altitude and 93° inclination. It was in the local time plane 0300-1500 during the period described here. The satellite was stabilized about three axes and the spectrometers were oriented at 55° to the local zenith so that they generally sampled precipitating particles



Kp
8
7
6
5
4
3
2
1
0
DST, gamma
0
-100
-200
AE, gamma
1000
500
200
100
50
20
10
SSC
SSC
12
16
20
0
4
8
12
16
20
0
4
8
12
16
20
0
DEC 16, 1971
DEC 17, 1971
DEC 18, 1971

FIGURE 1

during their traversals of the auroral and sub-auroral regions. The nine energies per unit charge sampled by the experiment were 0.74, 1.01, 1.41, 2.14, 2.92, 4.07, 6.3, 8.6, and 12.1 keV. Mass-per-unit-charge scans at each of these values were obtained in 6.14 seconds. Representative mass-per-unit charge distributions are given in Shelley et al. [1972] which also contains a more detailed description of the experiment and preliminary results from this same storm-time period.

ANALYSIS AND RESULTS

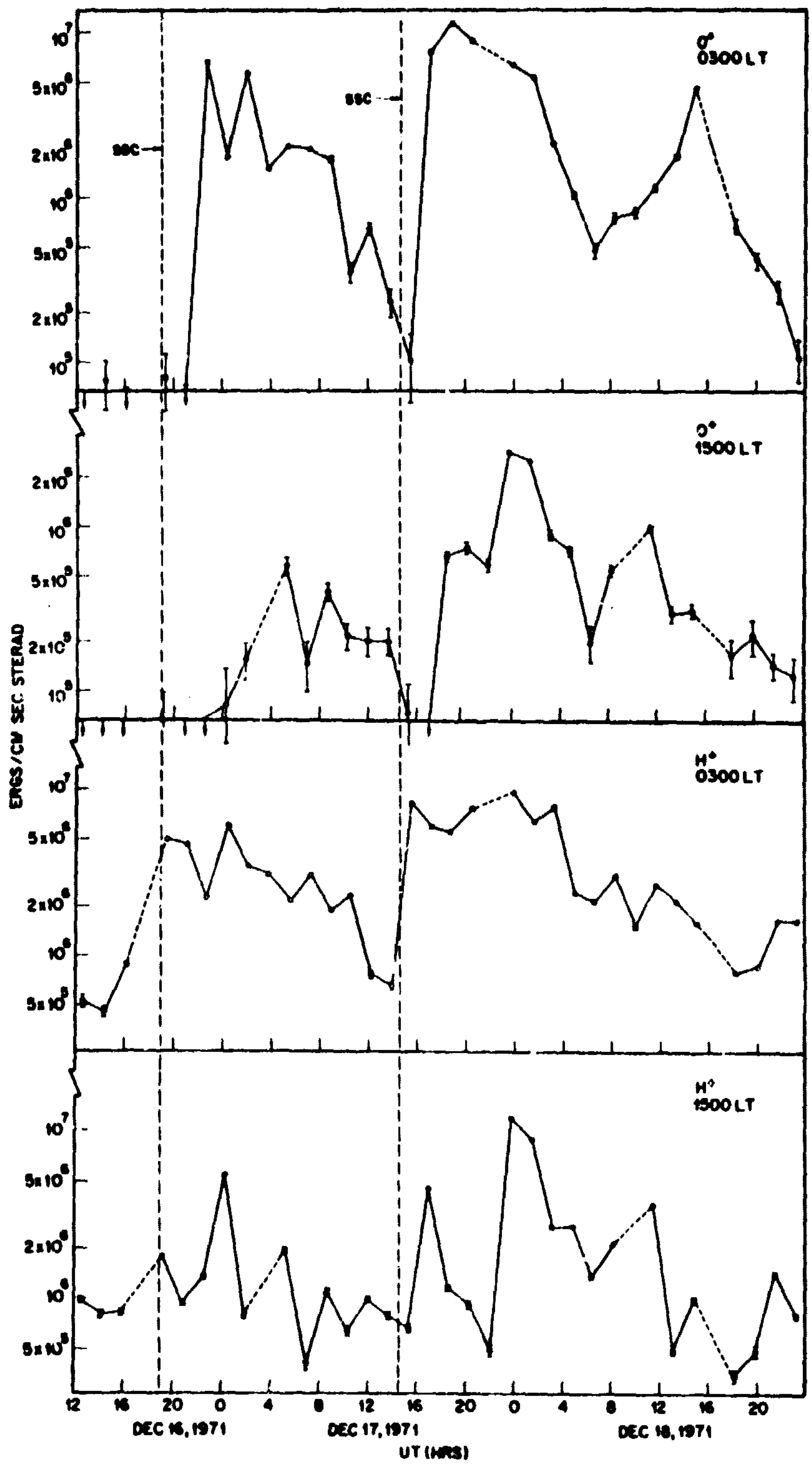
In order to investigate the variations in the properties of the ion fluxes on a time scale appropriate to the period of the storm, we have formulated a group of parameters based on the average or integral fluxes during a single complete traversal of the northern precipitation zone. This gives us a measurement in each of the northern precipitation zones (day and night) about every 100 minutes which is comparable to the time resolution of the various geomagnetic indices characterizing the disturbed period. To formulate these parameters for both the O^+ and H^+ ions we have summed the counts in the region of peak response in the mass-per-unit-charge sweep for each ion species and subtracted the background from an equivalent number of channels. Then for each six-second measurement cycle, we have computed the integral energy flux and average energy for each species in the energy range $0.7 \le E \le 12$ keV. For the intensity parameter, we have integrated the flux over the range in invariant latitude $44^\circ \le \Lambda_L \le 80^\circ$. For the hardness parameter we have computed the average energy of each ion

species over the same interval. To characterize the location of the precipitation zone we have computed the invariant latitudes at which 10%, 50%, and 90% of the energy flux latitudinal integrals were reached.

The results for the northern hemisphere observations during the period 1200 UT on December 16 to 2400 UT on December 18, 1971 are presented in Figures 2 through 5. Figure 2 shows the integral energy flux values. They have been multiplied by the satellite velocity and corrected for the (generally small) deviations of the trajectory from meridians of magnetic longitude so that they are an approximation to the instantaneous value of the energy flux precipitating through a one-cm-wide slit aligned perpendicular to the precipitation zone. The error bars represent counting statistics only. There are additional experimental uncertainties, discussed by Shelley et al. [1972, 1975], which we estimate as approximately ± 35%.

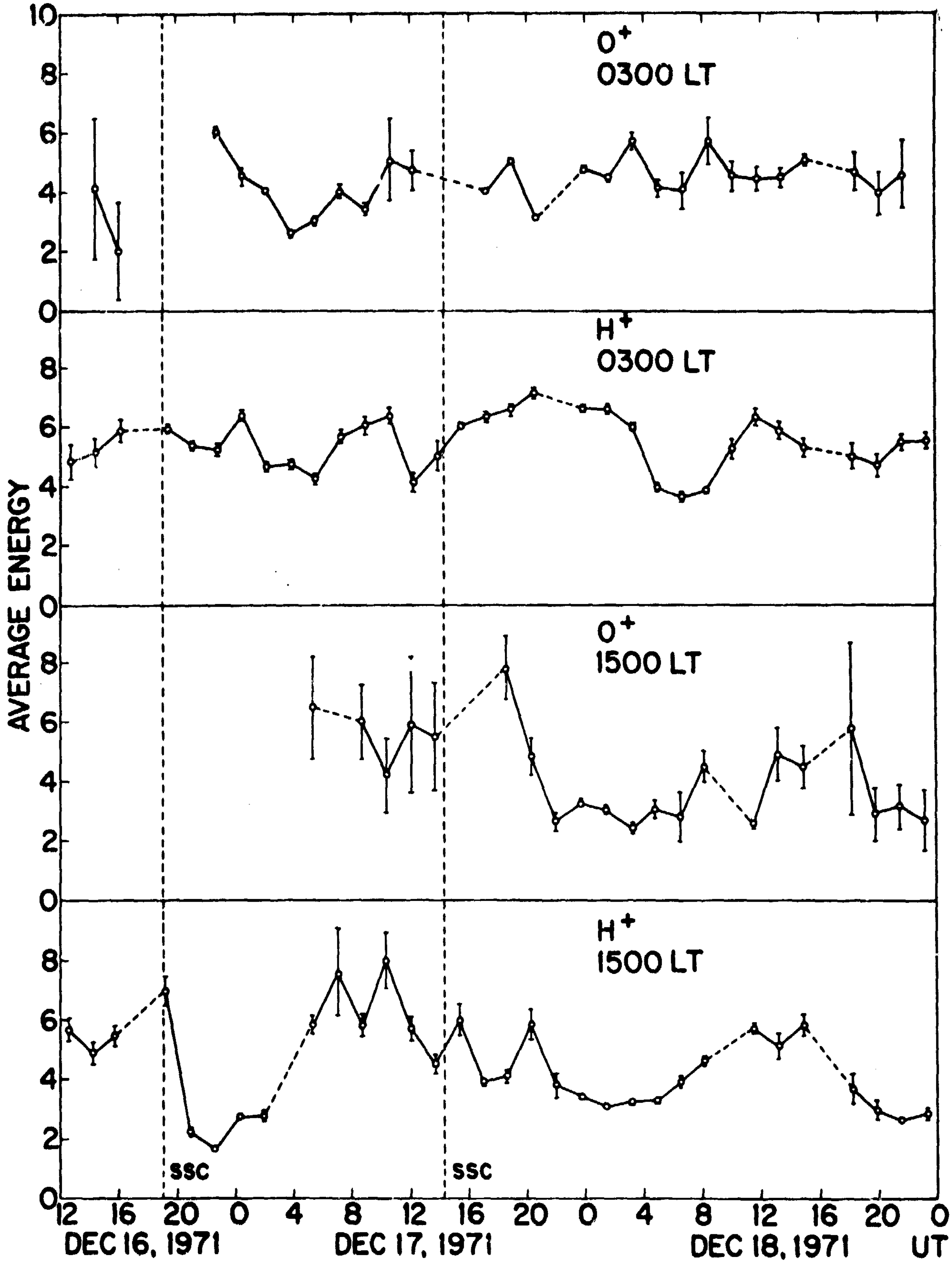
One sees in Figure 2 that there is a general correspondence between the O^+ zone integrals and the magnetic activity indices shown in Figure 1 with large flux increases being observed shortly after the sudden commencements. The nightside (0300 LT) O^+ increase leads the dayside (1500 LT) increase and lags the H^+ increase by over an hour in each storm. On the nightside, the O^+ and H^+ intensity levels are generally comparable while on the dayside the O^+ precipitation is considerably weaker than the H^+ precipitation in this energy range.

Figures 3 and 4 show the zone average energy values. For Figure 3, we defined the average ion energy as the ratio of the zone integral energy flux divided by the zone integral number flux. For those cases where the latter was less than two standard deviations above zero the average energy values



O⁺ 0300 LT
O⁺ 1500 LT
H⁺ 0300 LT
H⁺ 1500 LT
SSC
SSC
ERGS/CM² SEC STERAD
DEC 16, 1971
DEC 17, 1971
DEC 18, 1971
UT (HRS)

FIGURE 2



AVERAGE ENERGY
O^+
0300 LT
H^+
0300 LT
O^+
1500 LT
H^+
1500 LT
SSC
SSC
10
8
6
4
2
0
12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0
DEC 16, 1971
DEC 17, 1971
DEC 18, 1971
UT

FIGURE 3

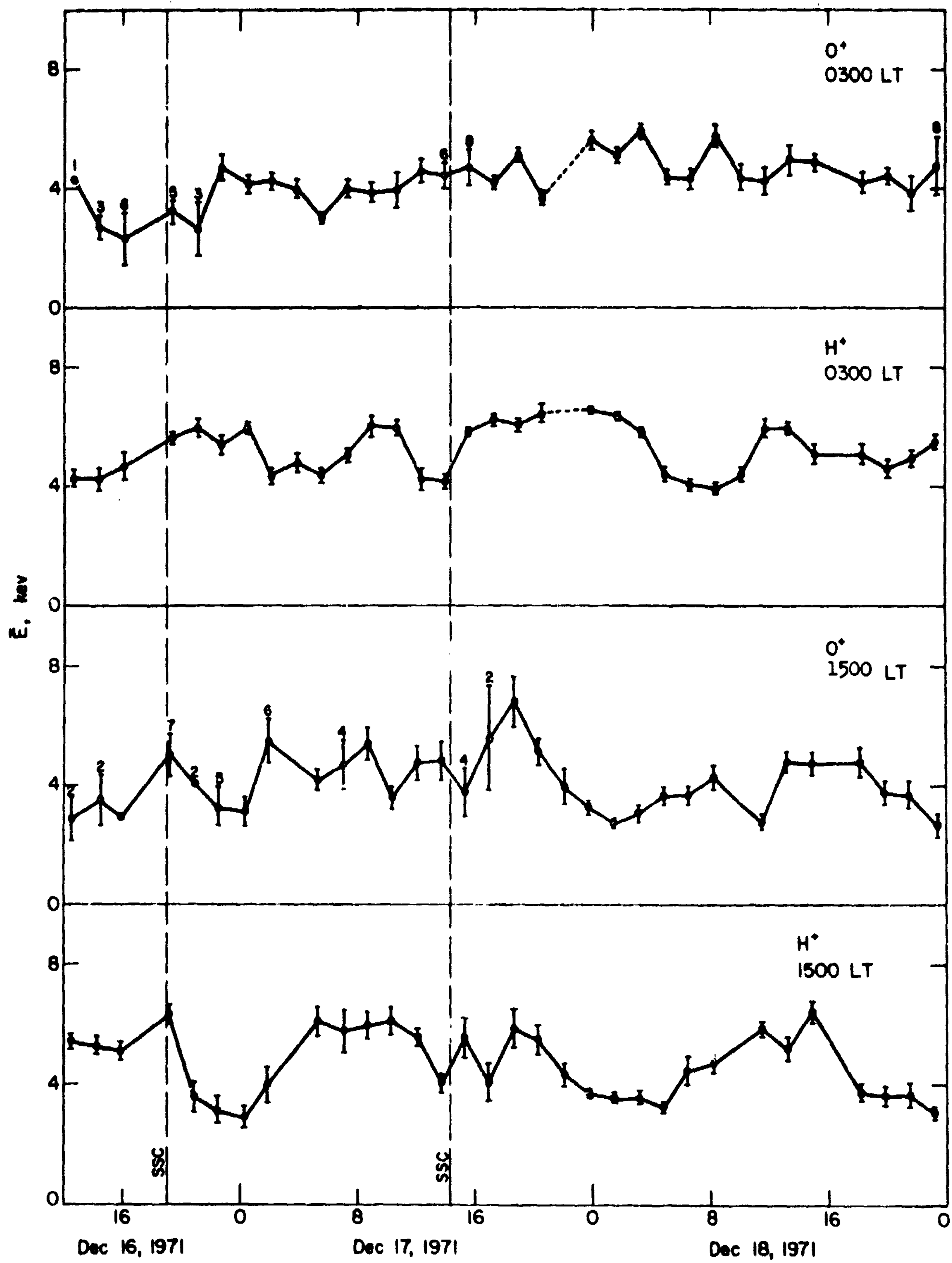

O+
0300 LT
H+
0300 LT
O+
1500 LT
H+
1500 LT
Ē, kev
8
4
0
SSC
SSC
16
0
8
16
0
8
16
0
Dec 16, 1971
Dec 17, 1971
Dec 18, 1971

FIGURE 4

were not considered significant and were deleted. The error bars represent counting statistics only. This definition for the average ion energy tends to give the most weight to the intense precipitation events in each zone crossing. In order to evaluate the significance of the observed trends we defined the alternative hardness parameter shown in Figure 4. For this parameter we computed the average energy for each individual (six-second) spectral measurement that was considered statistically significant and then computed the grand average value of these quantities over the precipitation zone, weighing each measurement equally. The significance criterion chosen was that the integral number flux in the individual measurement had to be greater than twice its standard deviation. The error bars in this figure represent the standard deviations of the means of these individual average energies and not counting statistics. For those cases where less than ten individual measurements were included, the number of measurements has been indicated on the figure. In examining Figures 3 and 4 we see that the average energies do not vary substantially between the two ion species or between the day and nightside measurements. There is a correspondence in the temporal variations of the O^+ and H^+ values on the dayside that is apparent in both Figures 3 and 4 so that we feel it is not the result of biasing due to a specific weighing technique. We will discuss the implications of this observation in the next section.

Figure 5 shows the locations of the precipitation zones. The center of the region, measured by the invariant latitude of the 50% point of the zone integral energy flux, is indicated with a circle for O^+ ions and a square for H^+ ions. The horizontal bars represent the extent of the region as

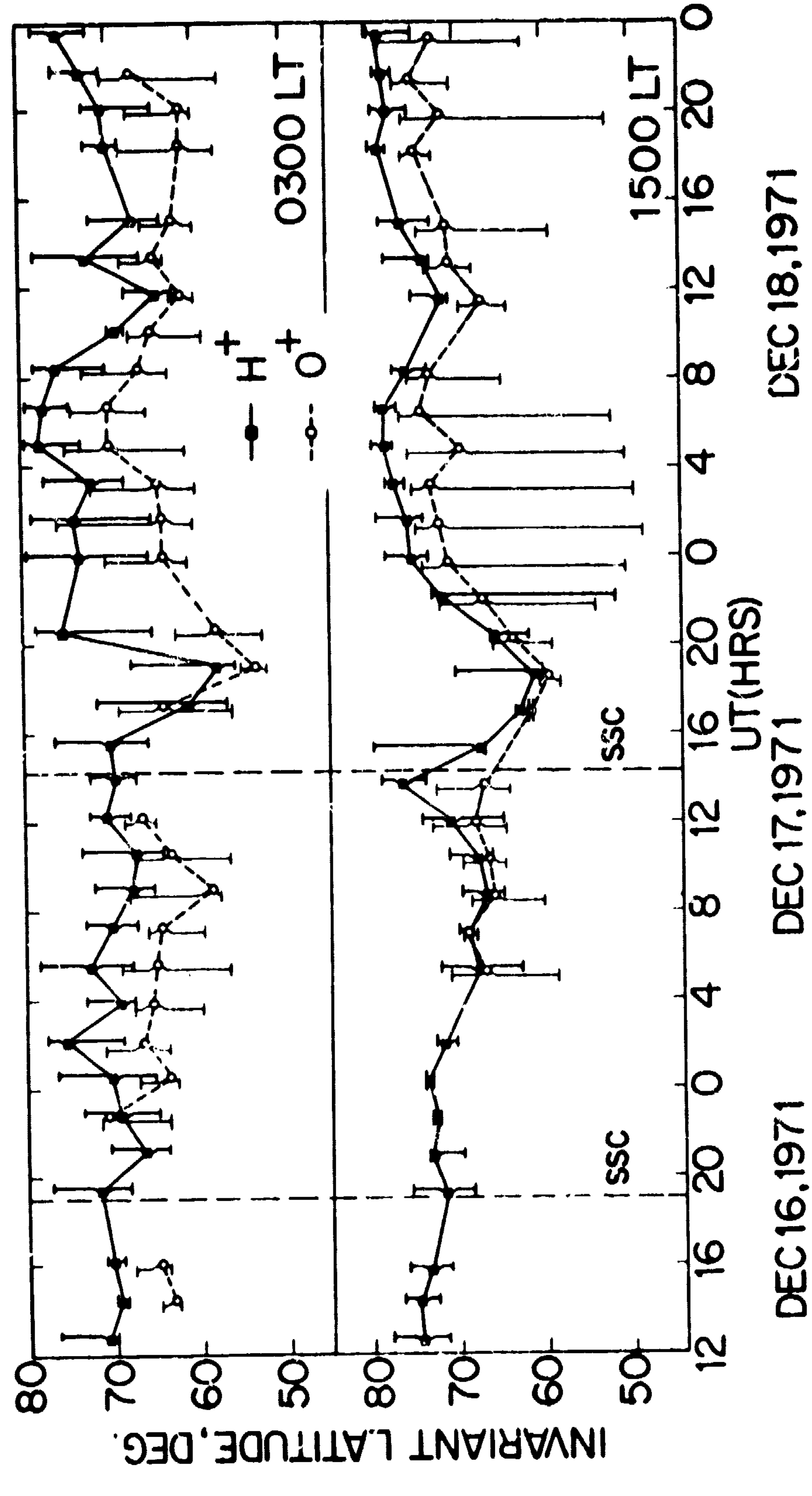

INVARIANT LATITUDE, DEG.
80
70
60
50
80
70
60
50
0300 LT
1500 LT
H+
O+
SSC
SSC
12
16
20
0
4
8
12
16
20
0
4
8
12
16
20
0
UT(HRS)
DEC 16,1971
DEC 17,1971
DEC 18,1971

FIGURE 5

measured by the 10% and 90% points in the same parameter. In several instances during this period the proton precipitation extended above 80° invariant latitude. The satellite orbit on some passes did not extend higher than 80° so in order to form a uniform data base we truncated the zone integrals at that latitude. Thus for those points in Figure 5 in which the upper bar is in the vicinity of 80°, that point does not necessarily mark the upper latitude of the precipitation region. Despite this distortion we see a detailed tracking of the precipitation zones of the two types of ions on both the day and nightsides. There is a latitudinal displacement between the two species with the O^+ zone generally located equatorward of the H^+ zone by several degrees. There is a correlation between the results at the two local times as well as between the two ion species.

DISCUSSION

As noted above in connection with Figure 2 the observed nightside O^+ fluxes are more intense than those on the dayside and there is a time delay in both storms between the initial O^+ increases on the night and daysides. This is suggestive of a longitudinal drift model with the principal injection occurring on the nightside. In the energy range of these measurements longitudinal drift is strongly affected by the corotation and convection electric fields. Shelley et al. [1974] showed from a study of the local time dependence of the O^+ ions that the median peak precipitated flux is about an order of magnitude higher in the LT interval 21-09 hours than it is in the interval 09-21 hours. The asymmetric location of the region of high

median intensities with respect to the midnight meridian is perhaps related to longitudinal drift since, according to most magnetospheric electric field models, there is a net eastward drift expected for trapped ions with energies of a few keV or less in the dawn section in this L range [Kavanagh et al., 1968; McIlwain, 1974]. If one looks at this hypothesis more quantitatively, however, one finds that the observed delay times are probably too short to be explained by a longitudinal drift of the O^+ ions from the local time sector of high-median peak intensities (21-09 hours). Consider first the December 17 storm for which the more definitive early-time dayside data were obtained. The time delay between the initial increases observed on the night and daysides is $\approx$ 1.4 hours. Depending upon the details of the magnetospheric electric field model and the specific particle energy, ions in the few-keV range injected in the midnight sector can longitudinally drift either eastward or westward. The shortest delay time expected for eastward drifting ions would be for those of 0 energy and this would be about five to ten hours for drift from 0900 to the observation point at 1500 LT [Kavanagh et al., 1968; McIlwain, 1974]. The shortest delay expected for westward drifting ions would be for the most energetic particles. Assuming E = 7.8 keV (the average energy of the initially observed dayside group) and L = 3.8 (the position of the median integral energy flux for this group) and neglecting convection for a lower limit we find that about nine hours would be required to drift from 2100 to 1500 LT for ions mirroring at low altitudes. For equatorially trapped ions, the corresponding time is about 6.5 hours. For the December 16 storm, there are possible ambiguities because of the low flux intensities and data gaps, but the time

delay between the initial increase on the night and daysides is most probably $\approx$ 3.2 hours. A similar drift calculation to that described above shows that a delay time of greater than 6.3 hours would be required for ions mirroring at low altitudes and 4.4 hours for equatorially mirroring ions. We conclude that the initially observed O^+ ions in both storms are not likely to be convected around from the nightside but more probably are accelerated locally. The observed delay times can perhaps be understood in terms of the time required for the energetic ring-current protons (a proposed energy source for the O^+ acceleration [Cladis, 1973a,b]) to drift around westward from the nightside sector. For example, equatorially-trapped 50-keV protons would drift from midnight to 1500 LT at L = 6 in about one hour.

If the initially observed O^+ ions on the dayside are indeed accelerated locally, this provides a significant constraint on models of the acceleration mechanism. It must be one that operates effectively under widely different ionospheric conditions to accelerate particles from both the day and nightside ionospheres.

Although the initially observed O^+ ions have apparently not convected from the nightside, those observed later in the storm might have done so. The observed softening in the average energy of the dayside O^+ ions about five hours after the initially observed nightside increase in the December 17 storm is in about the right period for the expected time of arrival of eastward convecting soft ions.

We have remarked on the general correspondence between the O^+ intensity parameters and the geomagnetic disturbance indices. To examine this relationship in more detail we have superimposed plots of the Dst and AE indices

and the nightside O^+ intensity parameter on the same logarithmic scale in Figures 6 and 7. For the Dst plot (Figure 6) we have inverted the ordinate so that increasing ring current intensity corresponds to increasing O^+ intensity. One sees that there is indeed a significant correlation between the various quantities throughout the period of the study indicating that the energized O^+ results from a strong coupling between the ionospheric source and the magnetosphere. The correlation with Dst is suggestive of a ring-current energy source as has been suggested by Cladis [1973a,b] and Brice and Lucas [1975], or alternatively that the O^+ ions contribute substantially to the ring current. On the other hand the correlation with AE suggests the possibility of a source associated with magnetospheric substorms, for example through the acceleration of the ionospheric ions by the field aligned electric fields expected to result from the anomalous resistivity caused by the enhanced Birkeland currents associated with substorms [Thorne, 1975]. O^+ ions have been reported during substorms by Johnson et al. [1975]. If the O^+ source mechanism were indeed proportional to the ring-current intensity (Dst) or the strength of electrojet activity (AE) and the O^+ ions were directly precipitated with negligible trapping lifetime, we would expect a detailed correspondence between the precipitated O^+ intensity and the appropriate geomagnetic index. We see in Figure 6 that the ring-current hypothesis fits reasonably well to the early-time data in both storms. The apparently shorter decay time for the O^+ intensity than for Dst and the large increase in O^+ intensity near 1500 UT on December 18 which is not reflected in Dst argues against this model for the later phases of the storm.

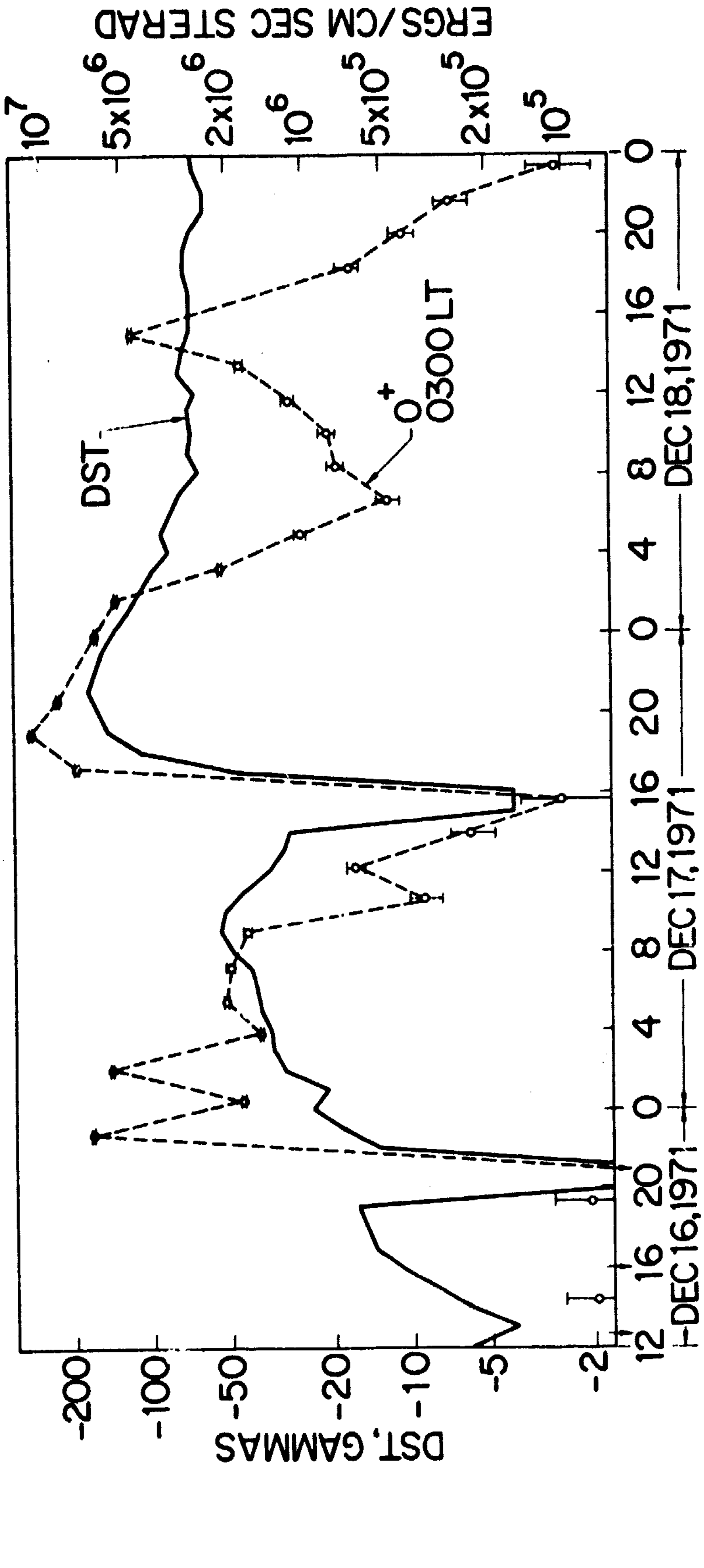

ERGS/CM SEC STERAD
10^7
$5x10^6$
$2x10^6$
10^6
$5x10^5$
$2x10^5$
10^5
DST
O^+
0300 LT
DST, GAMMAS
-200
-100
-50
-20
-10
-5
-2
12 16 20 0 4 8 12 16 20 0 4 8 12 16 20 0
DEC 16,1971
DEC 17,1971
DEC 18,1971

FIGURE 6

The substorm hypothesis relevant to Figure 7 also gives a rough qualitative fit to the observations. In particular, we note the corresponding peaks in the two parameters around midday on the 18th. We would, however, hesitate to conclude that the correlation with AE shown in Figure 7 is definitely superior to that with Dst in Figure 6 on the basis of this limited amount of data.

A model utilizing a ring-current energy source that would allow for different decay times for the observed O^+ intensity and the Dst index is one in which the observed O^+ is precipitating from a trapped parent population which is controlled by decay processes different from those for the energetic protons which presumably are primarily responsible for the ring current, at least at later times in the storm [Berko et al., 1975].

The best estimate of the O^+ decay time to use for these considerations is probably obtained from the data in the 0000-0600 UT time period on December 18 when both AE and Dst are declining nearly monotonically and injection processes are presumably weak. We find that in this period the nightside O^+ precipitation is falling off with about a 2-1/2 hour time constant. This is substantially shorter than the estimated decay time resulting from strong pitch-angle diffusion or charge exchange for a longitudinally uniform trapped population of O^+ ions. For the nightside O^+ data, the invariant latitude of the median integral energy flux varies from 64° to 70° during this period and the average O^+ energy is about 4.5 keV. The minimum lifetime for strong pitch-angle diffusion corresponding to these values for O^+ ions varies over the range from approximately 17 to 78 hours [Kennel, 1969]. The appropriate charge exchange lifetime for equatorially mirroring O^+ ions is greater than

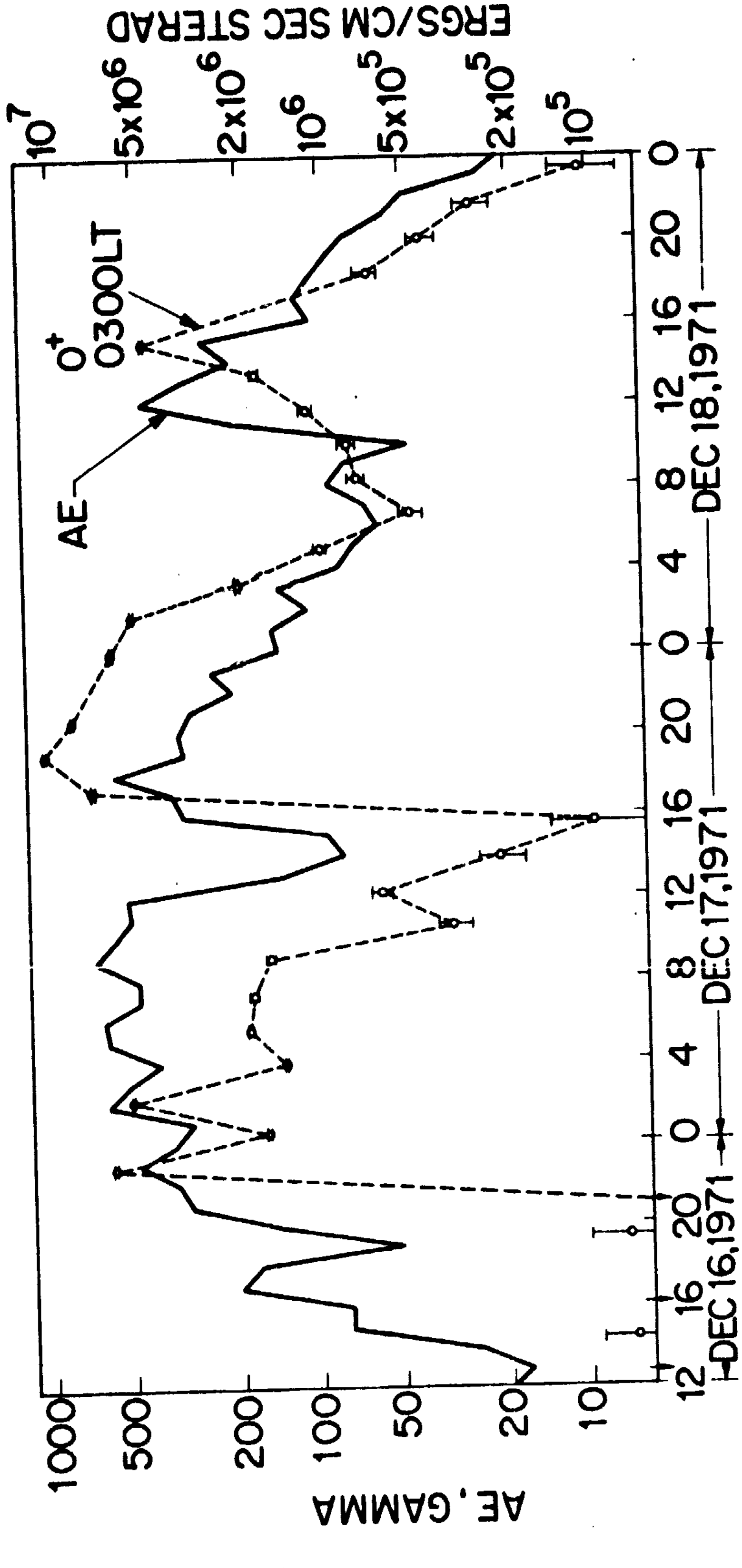

ERGS/CM SEC STERAD
10^7
5x10^6
2x10^6
10^6
5x10^5
2x10^5
10^5
O+
0300LT
AE
AE, GAMMA
1000
500
200
100
50
20
10
12
16
20
0
4
8
12
16
20
0
4
8
12
16
20
0
DEC 16,1971
DEC 17,1971
DEC 18,1971

FIGURE 7

four days based on the lifetimes for proton charge exchange given by Swisher and Frank [1968] modified by the ratio of the charge exchange cross sections for H^+ on H and O^+ on H summarized in Fite et al. [1962].

Let us consider two simple trapping models that attempt to explain both the observed O^+ decay time and the asymmetry in the local time distribution of peak O^+ intensities reported by Shelley et al. [1974], assuming a symmetric injection region around midnight. For the first model we assume that the O^+ ions are trapped but precipitating under strong pitch-angle diffusion so that the time dependence of the O^+ intensity parameter also represents the time dependence of the trapped flux intensity at 0300 LT. Consider the decay of a longitudinally limited cloud of ions injected into the 2100-0300 LT sector. The lifetime of the population at 0300 LT is determined by both precipitation and the depletion of the trapped population by longitudinal drift and convection. A detailed convection calculation is beyond the scope of this work but we can get some idea of the time scales involved by considering the motion of zero energy ions using current magnetospheric electric field models [McIlwain, 1972, 1974]. A cloud of such ions with the local time extent assumed above would take of the order of an hour to convect past the observation point at 0300 LT. More energetic ions would take longer because their gradient and curvature drifts oppose the convection motion. Depending on the details of the assumed electric fields, ion energies, and pitch-angle distributions and including the effect of precipitation, the model could probably be fit to the observed O^+ decay time.

The decrease in the local time distribution of peak flux intensities at $\approx$ 0900 LT reported by Shelley et al. [1974] might be interpreted in this

model as resulting from the decay of the trapped population through precipitation in the time it takes to convect from the injection region to 0900 LT. For this to occur the convection time would have to be comparable to the precipitation lifetimes and this seems somewhat long, but not clearly excluded. Some local acceleration on the dayside would still be required in this model to explain, for example, the small time delay observed between the rise of the dayside and nightside O^+ fluxes shown in Figure 2.

For our second model, let us assume again that the observed O^+ ions are precipitating from a parent trapped population but that the precipitation is not necessarily proportional to the trapped flux intensity. We can assume, for example, that during the recovery phase the strength of pitch-angle diffusion declines and the observed 2-1/2 hour time constant is not representative of the decay of the trapped flux intensity but of the precipitation mechanism. The extent toward morning of the local time asymmetry could then be determined by how far the O^+ ions convect in the time period when the precipitation mechanism is most effective. In the storms described here, the time from the initial O^+ increase until the flux begins to fall off more rapidly than Dst is about 10 to 12 hours. Again, this is getting into the range where a fit to a convection calculation appears possible depending on the details of the model.

The correlations between the protons and the O^+ ions apparent in Figures 3 to 5 apply additional constraints to these phenomenological models. The tracking of the location of the two precipitation zones could arise from common motions of trapped populations of the two species; from a process in which the O^+ ions were energized by a mechanism involving the

trapped protons as an energy source; or from a process in which the protons and O^+ ions were accelerated together from the ionosphere by the same mechanism. In the latter two cases a substantial trapped O^+ population would not necessarily be involved. The correlations in the variations in average energies of the two species on the dayside seem most directly interpretable in terms of storm-associated acceleration processes acting upon the parent trapped populations, or with a common ionospheric source and a common acceleration mechanism varying in efficiency during the storm-time period. This latter interpretation would have far-reaching effects on the present state of thinking about the origin of the energetic magnetospheric proton population [Hill, 1974].

We have briefly explored a few of the constraints which these morphological results can exert on possible source and energization mechanisms for the O^+ ions. It is hoped that more quantitative models will be investigated by others utilizing the experimental results presented here and in Paper II.

As discussed in the "Analysis and Results" section, the zone integral intensity values can be considered as an approximation to the energy flux precipitating into a one-cm-wide strip transverse to the precipitation zone. If we knew the local time distribution of the fluxes, we could estimate the instantaneous worldwide precipitated ion flux in this energy range during the course of the storm. The local time distribution of precipitating protons can be estimated from the H_β observations of Eather and Mende [1971] and Mende (private communication). A rough estimate for the local time distribution of the O^+ ions can be obtained from the work of Shelley et al. [1974]. From these results we find that a reasonable approximation to the

local time average of the flux intensity can be formulated from the average of our measured values at 1500 and 0300 hours local time. By assuming conjugacy and isotropic pitch-angle distributions over the upper hemisphere, we can approximate P, the total worldwide precipitated energy flux in the range ($0.7 \le E \le 12$ keV) as

$$P \approx 2\pi^2 R_E (F_N \cos \Lambda_N + F_D \cos \Lambda_D) \text{ ergs/sec}$$

where F = the zone integral energy flux (Figure 2), Λ = the invariant latitude of the 50% point of the zone integral (Figure 5), and the subscripts D and N refer to day (1500 LT) and night (0300 LT), respectively. Plots of P for both the H^+ and O^+ ions are given in Figure 8.

If we assume that the precipitating ion fluxes originate from (or derive their energy from) the trapped population responsible for the stormtime ring current we can ask what fraction of the ring-current energy is lost through ion precipitation. The instantaneous value of Dst can be related to the total energy content of the trapped ring-current particles (E) by the expression $Dst(\gamma) = 2.6 \times 10^{-21}$ E, where E is given in ergs [Sckopke, 1966; Frank, 1967].

In order to have directly comparable quantities we would like to make the comparison between P and changes in Dst in a time period when ring-current injection processes are negligible. Davis and Parthasarathy [1967] have shown that during such periods AE is relatively low and Dst decays exponentially with a time constant of about ten hours. The time period from 0000 to 0800 UT on December 18 fulfills these conditions. During this period 2.8×10^{22} ergs

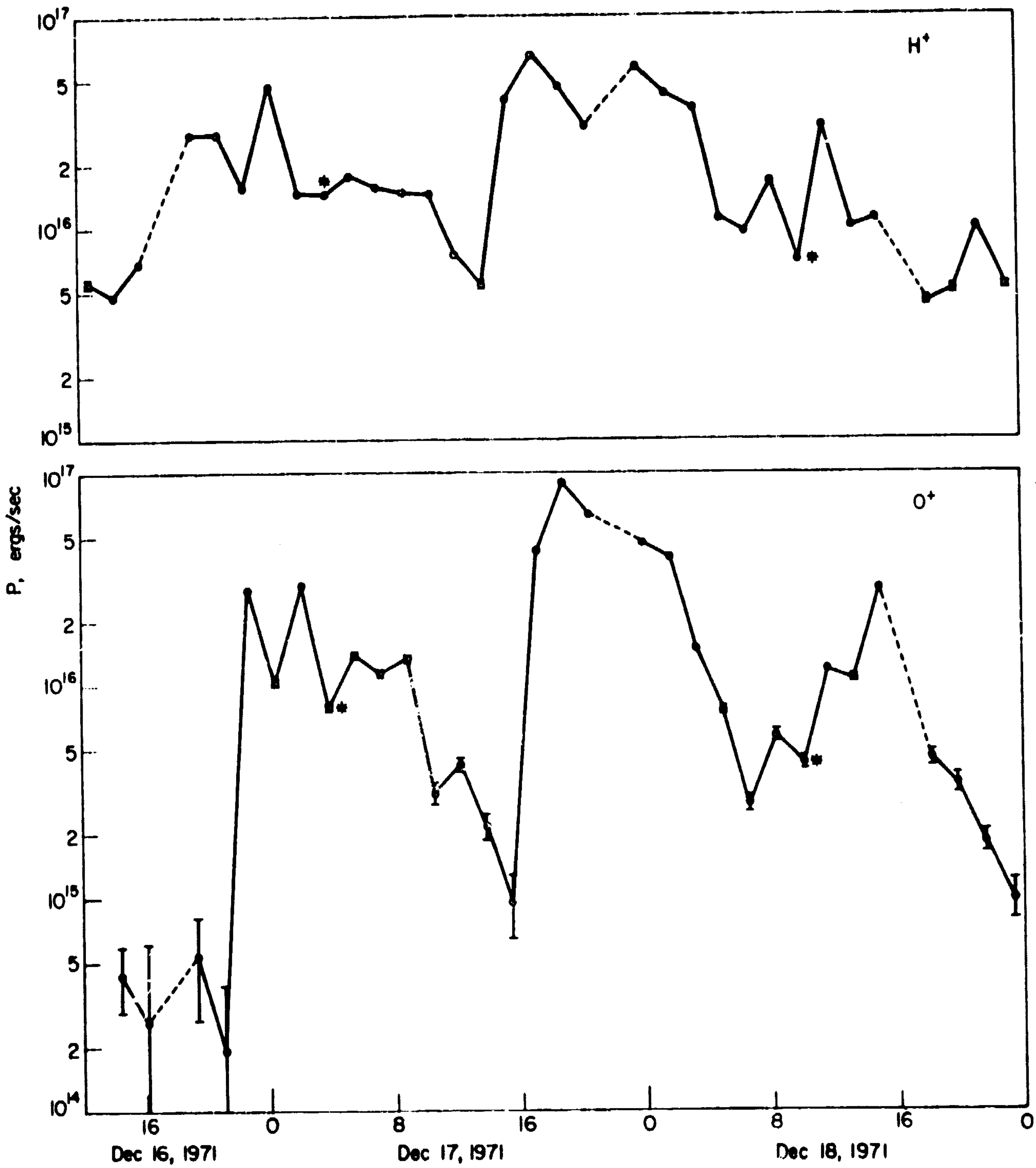

H+
O+
P, ergs/sec
10^{17}
5
2
10^{16}
5
2
10^{15}
5
2
10^{14}
16
0
8
16
0
8
16
0
Dec 16, 1971
Dec 17, 1971
Dec 18, 1971

FIGURE 8

are lost from the ring current according to the above relationship. By integrating the curves in Figure 8 over this interval, we find that the worldwide energy loss from precipitating ions with energy between 0.7 and 12 keV is 6×10^{20} ergs of O^+ ions and 8×10^{20} ergs of protons, thus accounting for about 5% of the lost ring-current energy.

The major portion of the ring current energy is carried by protons with energies above the range o: our spectrometer. For a first-order estimate of the energy loss in this portion of the spectrum, we can utilize the Explorer 45 measurements of trapped protons in the energy range from 1-500 keV taken during this same time period at the latitude of the maximum of the equatorial energy density of the particles ($L = 3.6$). Integrating the orbit 102 spectrum in Figure 3 of Smith and Hoffman [1973] we find that only 9% of the energy density is carried by protons with energies less th.n 12 keV. If we assume that this spectrum is applicable to both the precipitating H^+ and O^+ ions we conclude that about 60% of the ring-current energy loss can be accounted for by precipitating ions. If we assume that the published spectrum is applicable only to the precipitating tons and that the spectr.m of the precipitating O^+ ions cuts off sharply at 12 keV, we still can account for about 40% of the ring-current energy loss in this way. It should be noted that the Explorer 45 spectrum averaged over the energy range $1 \le E \le 12$ keV gives an average energy which is consistent with the average energy of the ions measured during this period with the 1971-089A experiment.

The Explorer 45 energy spectrum which we have utilized was constructed with data from two types of instruments. The lower energy p.otion ($E < 30$

kev) was measured with an electrostatic analyzer which would have counted any O^+ ions in the equatorial plane. The upper energy portion was measured with solid-state detectors which are relatively insensitive to O^+ ions because of the increased losses of the heavier ions in the dead layer of the detector. By utilizing the spectrum as published we have essentially assumed that the equatorially trapped O^+ fluxes are negligible during this period. An alternative assumption is that the O^+ fluxes have a similar equatorial pitch-angle distribution to that of the protons. In this case we would modify the published spectrum at the low energies by deleting the O^+ contribution according to the H^+/O^+ ratio measured at low altitudes during this period.

Under this assumption only 6% of the trapped proton energy density is carried by protons with energies below 12 keV and either about 80% or 50% of the ring current energy loss is accounted for by precipitating ions during this period according to the two assumptions on the O^+ spectrum discussed above.

As indicated, these are only meant to be rough estimates. It appears, however, that under the stated assumptions we can conclude that ion precipitation was an important loss mechanism for the ring-current energy during this storm. If a large fraction of the precipitating ions derive their energy from sources other than the ring current, this conclusion is of course not valid. One obvious such source is the magnetosheath which is known to contribute to the dayside proton precipitation at high latitudes [Heikkila and Winningham, 1971]. We do not feel that the polar cleft particles contribute substantially to the measured integrals however; since,

as will be seen in Paper II, the average proton energies even at high latitudes on the dayside remain in the few-keV range, well above the average proton energy in the cusp. In any case, even deleting the dayside proton data completely would only reduce the above estimates by about 25%.

Our conclusions about the importance of ion precipitation as a loss mechanism in this storm are in disagreement with the conclusions of Mizera [1974] for the March 19-20, 1969 magnetic storm. The details of his calculation were not presented, but on the basis of electrostatic analyzer data he concluded that less than 1% of the ring-current energy lost during that storm could be attributed to precipitating protons with E > 12 keV.

SUMMARY AND CONCLUSIONS

Some of the principal results of this study of the zone integral parameters of the precipitating O^+ and H^+ ions during the December 16-18, 1971 storm period are:

1) The intensity of the precipitating O^+ ions was found to be well correlated with the geomagnetic indices which measure the strength of magnetospheric substorm activity and the strength of the storm-time ring current. Since the O^+ ions are almost certainly of ionospheric origin, these correlations indicate that a previously unknown strong coupling mechanism existed between the magnetosphere and the ionosphere during the period of the study.

2) The storm-associated initial increase of the O^+ ions on the nightside (0300 LT) was found to lead that on the dayside (1500 LT) and

lag the initial nightside H^+ increase by more than one hour in both storms. A consideration of ionic transport processes leads to the conclusion that the mechanism accelerating the O^+ ions is probably operative in the dayside as well as the nightside ionosphere. This is significant in that it implies that this unknown mechanism can be operative over a wide range of ionospheric and magnetospheric conditions.

3) Correlations have been found between the locations of the O^+ and H^+ precipitation zones and between the average energies of the two ionic species. From these and other morphological features, it is inferred that the O^+ ions are probably either accelerated together with the protons or coexist with them as a trapped population for an extended period. Either of these hypotheses imply that the ionospheric contribution to the storm-time ring current may be more significant than has previously been considered.

4) The total worldwide precipitated ion energy flux has been estimated during the period of the study and compared to the ring-current energy content as measured by Dst. The comparison indicates that ion precipitation was an important loss mechanism for ring-current energy during the 17-18 December 1971 magnetic storm.

ACKNOWLEDGMENTS

We would like to thank D. L. Carr for his assistance with the data reduction and analysis. The satellite experiment was supported by the Defense Nuclear Agency through the Office of Naval Research. This anal-

ysis has been supported by the Air Force Office of Scientific Research under Contract F44620-73-C-0050, by NASA under Contract NASw 2777, and by the Lockheed Independent Research program.

REFERENCES

Berko, F. W., L. J. Cahill, Jr., and T. A. Fritz, Protons as the prime contributors to the storm time ring current, J. Geophys. Res., 1975 (in press).

Brice, N., and C. Lucas, Interaction between heavier ions and ring current protons, J. Geophys. Res., 80, 936, 1975.

Cladis, J. B., Effect of magnetic field gradient on motion of ions resonating with ion cyclotron waves, J. Geophys. Res., 78, 8129, 1973a.

Cladis, J. B., Interpretation of energetic heavy ion fluxes observed during the magnetic storm of December 17, 1971, Radio Science, 8, 1029, 1973b.

Davis, T. N., and R. Parthasarathy, The relationship between polar magnetic activity DP and growth of the geomagnetic ring current, J. Geophys. Res., 72, 5825, 1967.

Eather, R. H., and S.B. Mende, Airborne observations of auroral precipitation patterns, J. Geophys. Res., 76, 1746, 1971.

Fite, W. L., A. C. H. Smith, and R. F. Stebbings, Charge transfer in collisions involving systematic and asymmetric resonance. Proc. Royal Soc., A268, 527, 1962.

Frank, L. A., On the extraterrestrial ring current during geomagnetic storms, J. Geophys. Res., 72, 3753, 1967.

Heikkila, W. J., and J. D. Winningham, Penetration of magnetosheath plasma to low altitudes through the dayside magnetospheric cusps, J. Geophys. Res., 76, 883, 1971.

Hill, T. W., Origin of the plasma sheet, Revs. Geophys and Space Phys., 12, 379, 1974.

Hoffman, R. A., Particle and field observations from Explorer 45 during the December 1971 magnetic storm period, J. Geophys. Res., 78, 4771, 1973.

Johnson, R. G., R. D. Sharp, and E. G. Shelley, Composition of the hot plasmas in the magnetosphere, Proceedings of the Nobel Symposium on the Physics of the Hot Plasma in the Magnetosphere, Kiruna, Sweden, April 2-4, 1975, Plenum Publ. Co., Ltd., 1975 (in press).

Kavanagh, L. D., Jr., J. W.Freemen, Jr., and A. J. Chen, Plasma flow in the magnetosphere, J. Geophys. Res., 73, 5511, 1968.

Kennel, C. F., Consequences of a magnetospheric plasma, Revs. Geophys., 7, 379, 1969.

Lyons, L. R., and D. J. Williams, Storm associated variations of equatori-ally mirroring ring current protons, 1-800 keV, at constant first adia-batic invariant, Space Environment Laboratory, NOAA, Boulder, Colorado, Preprint No. 187, 1975.

McIlwain, C. E., Plasma convection in the vicinity of the geosynchronous orbit, in Earth's Magnetospheric Processes, B. M. McCormac, ed., D. Reidel Publ. Co., Dordrecht, Holland, p. 268, 1972.

McIlwain, C. E., Substorm injection boundaries, in Magnetospheric Physics, B. M. McCormac, ed., D. Reidel Publ. Co., Dordrecht, Holland, p. 143, 1974.

Mizera, P. F., Observation of precipitating protons with ring current ener-gies, J. Geophys. Res., 79, 581, 1974.

Skopke, N., A general relationship between the energy of trapped particles and the disturbance field near the earth, J. Geophys. Res., 71, 3125, 1966.

Sharp, R. D., and R. G. Johnson, Some average properties of auroral electron precipitation as determined by satellite observations, J. Geophys. Res., 73, 969, 1968.

Sharp, R. D., D. L. Carr, and R. G. Johnson, Satellite observations of the average properties of auroral particle precipitation: latitudinal variations, J. Geophys. Res., 74, 4618, 1969.

Sharp, R. D., R. G. Johnson, and E. G. Shelley, Energetic O^+ ions in the magnetosphere, J. Geophys. Res., 79, 1844, 1974.

Shelley, E. G., R. G. Johnson, and R. D. Sharp, Satellite observations of energetic heavy ions during a geomagnetic storm, J. Geophys. Res., 77, 6104, 1972.

Shelley, E. G., R. G. Johnson, and R. D. Sharp, Morphology of energetic O^+ in the magnetosphere, in Magnetospheric Physics, B. M. McCormac, ed., D. Reidel Publ. Co., Dordrecht, Holland, p. 135, 1974.

Shelley, E. G., R. D. Sharp, and R. G. Johnson, He^{++} and H^+ flux measurements in the dayside cusp: estimates of the convection electric field, J. Geophys. Res., submitted 1975.

Smith, P. H., and R. A. Hoffman, Ring current particle distributions during the the magnetic storms of December 16-18, 1971, J. Geophys. Res., 78, 4731, 1973.

Swisher, R. L., and L. A. Frank, Lifetimes for low-energy protons in the outer radiation zone, J. Geophys. Res., 73, 5665, 1968.

Thorne, R. M., Wave particle interactions in the magnetosphere and ionosphere, Revs. Geophys. and Space Phys., 13, 291, 1975.

Williams, D. J., Hot plasma dynamics within geostationary altitudes, Proceedings of the Nobel Symposium on the Physics of the Hot Plasma in the Magnetosphere, Kiruna, Sweden, April 2-4, 1975, Plenum Publ. Co., Ltd., 1975 (in press).

Williams, D. J., and L. R. Lyons, The proton ring current and its interaction with the plasmapause: storm recovery phase, J. Geophys. Res., 79, 4195, 1974a.

Williams, D. J., and L. R. Lyons, Further aspects of the proton ring current interactions with the plasmapause: main and recovery phases, J. Geophys. Res., 79, 4791, 1974b.